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Solar and Net Radiation for Estimating Potential Evaporation from Three Vegetation Canopies

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Summary: *Solar and net radiation data are frequent/y used in estimating potential evaporation (PE) from various vegetative surfaces needed for water balance and hydrologic modeling studies. Weather parameters such as air temperature, relative humidity, wind speed, solar radiation, and net radiation have been continuous/y monitored using automated sensors to estimate PE for three different vegetation canopies in the coastal plain of North Carolina. Mean daily solar radiation, among these three stations varied within about 10 percent on/y. Mean daily net radiation on pine forest canopy was at /east 24% higher than on grass vegetation at the same /a titude, indicating that use of net radiation from a forest site in Penman based methods may we// overestimate the PE for a grass vegetation. Tests of self-calibration procedure by A//en (1997) and method of Hargreaves-Samani (1982) for estimating daily and month/y solar radiation at these coastal sites revealed that the former is more accurate and reliable than the later. The regression relationship developed using net and solar radiation for grass was different from the one reported in the literature for Bermuda grass in North Carolina.*

Keywords: Penman-Monteith REF-ET, Extraterrestrial Radiation, Hydrologic Modeling, Loblolly Pine, Coastal North Carolina.

Solar and Net Radiation for Estimating Potential Evaporation from Three Vegetation Canopies

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Abstract

Solar and net radiation data are frequently used in estimating potential evaporation (PE) from various vegetative surfaces needed for water balance and hydrologic modeling studies. Weather parameters such as air temperature, relative humidity, wind speed, solar radiation, and net radiation have been continuously monitored using automated sensors to estimate PE for three different vegetation canopies in the coastal plain of North Carolina. Mean daily solar radiation, among these three stations varying in latitude from 34° 48' N to 35° 50' N, was barely different. However, mean daily solar radiation above emerging vegetation was consistently higher by about 10 %, depending upon the years, compared to short grass vegetation on an agricultural site. Mean daily net radiation on pine forest canopy was at least 24 % higher than on grass vegetation at the same latitude, indicating that use of net radiation from a forest site in Penman based methods may well overestimate the PE for a grass vegetation. However, net radiation for the emerging vegetation was found to be only 3 % less than that for pine forest. Tests of self-calibration procedure by Allen (1997) and method of Hargreaves-Samani (1982) for estimating daily and monthly solar radiation at these coastal sites revealed that the former is more accurate and reliable than the later. Compared to daily values the monthly estimates were in better agreement with measured data. Daily relationships of solar versus net radiation developed with these data resulted in slopes and intercept parameters of 0.65, -1.38 for short grass, 0.69, -0.85 for wetland vegetation, and 0.75, -1.44 for the pine forest, respectively. This relationship for grass was different from the one reported in the literature for Bermuda grass in North Carolina. These methods of estimating solar radiation and new relationships for net radiation data for the humid coastal plain may have big implications on estimates of PE used in hydrologic and water quality modeling.

Introduction

Evapotranspiration (ET) is one of the major components of the water balance in the hydrologic cycle. In most of the hydrologic water and nutrient budgets ET is calculated based on the potential evaporation (PE) or reference evapotranspiration (REF-ET), a term synonymous to potential ET (PET) for a reference crop or vegetation (Jensen et al., 1990; Amatya et al., 1995). A large number of hydrologic rainfall/runoff and water quality models include PET as one of the primary input variables. Reliability of hydrologic predictions depends upon the accuracy of the PET data used in the model. This is especially true during the summer-fall period when ET demands are high.

Estimates of PET can be obtained by direct measurements using pan evaporation or by using measured meteorological variables in mathematical equations to predict monthly or daily values. The equations or models vary from simple empirical relationships to complex methods based on physical processes such as the Penman-Monteith (1964) method (the P-M method). The P-M method for estimating PET with reference to the characteristics and surrounding of the crop has been extensively studied with great success in a wide array of geographical and climatological conditions. Therefore, it has been accepted as the best performing combination equation in the absence of measured PET data (Amatya et al., 1995; Jensen et al., 1990).

Although the P-M method is widely accepted for its reliability, it is often discarded because of large amount of weather input parameters that are not frequently available for most of the weather stations. One such parameter is net radiation (R_n) which is the most sensitive parameter for estimating PE using the P-M method and therefore, needs to be accurately estimated (Amatya, 1993; Beven, 1979;

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Smajstrla and Zazueta, 1994). When measured R_n is not available, it is often estimated based on solar radiation (R,).

The National Weather Service (NWS) Class A weather stations measure sunshine hours and dew point temperature that are generally used for estimating solar and net radiation as was shown by Amatya et al. (1995) for a station at Wilmington in coastal North Carolina. There are only two such stations in eastern North Carolina including Cape Hatteras on the Outer Banks. Other stations (e.g. Cherry Point in eastern North Carolina) monitor percent cloud cover as a parameter for estimating solar radiation. Jensen et al. (1 990) stated that more reliable solar radiation estimates are obtained by recorded percent sunshine data as compared to cloud cover data as the later is more qualitative. In a recent study Lindsey and Farnsworth (1997) also reported that the long term PE estimates using the cloud cover based solar radiation are biased with significantly lower values than those obtained by using direct measurements of solar radiation or using percent sunshine. The authors also suggested a method to correct for such a bias. Other researchers have also developed and evaluated alternative methods of estimating solar radiation from easily measured parameters such as air temperature (Stockle and Bellocchi, 1999; Allen, 1997; Ndlovu et al., 1993). Net radiation for the P-M method is then calculated using dew point and air temperature or simply the empirical relationship using solar radiation reported in the literature. These relationships may vary from region to region and also may be dependent upon vegetative surface and season. Jensen et al. (1990) published such relationships for various locations in the US and the world. Amatya et al. (1995) used the published relationships with measured solar radiation to estimate the net radiation and vice versa for evaluating five different methods of estimating REF-ET in eastern North Carolina.

The main objectives of this paper are: (a). to compare the daily solar and net radiation measured on three different vegetative canopies, (b). to test the empirical relationships of estimating solar radiation from temperature data that were originally developed for semi-arid regions (Hargreaves-Samani, 1982) and (c) to develop relationships of net and solar radiation using weather data measured above three different vegetation canopies and compare with the literature data. The data and methods tested herein will provide a basis for evaluation of reliability of extrapolated radiation data in estimating REF-ET in the humid coastal plain of North Carolina. This work is a continuation of the previous study by Amatya et al. (1995) on comparison of methods for estimating REF-ET for eastern North Carolina.

Site Description and Methodology

Weather data from three coastal stations in eastern North Carolina were used for this study. A general description of these stations is shown in Table 1. The climatic characteristics of these coastal sites have been described by Amatya et al. (1995). The long-term average annual maximum and minimum air temperatures for these locations vary between 22.8' C to 22.3' C and 9.2° C and 12.5' C, respectively. Generally, the maximum temperatures occur during the months of June, July, and August when the region may experience large amounts of rainfall due to intense summer storms and hurricanes.

The first station is located at the experimental pine forest owned and managed by the Weyerhaeuser Company in Carteret County. The data reported by Amatya et al. (1995) for this site for the period 1988 through 1992 were collected at a weather station above a grass vegetation located 800 m away from the current station. Weather data collected from the old station through 1997 were used in the hydrologic modeling of a drained pine plantation studied by Amatya and Skaggs (2000). A new weather station with a Campbell Scientific CR1 OX data logger was later installed in the middle of one of the three experimental watersheds in late October 1997. The station is a 3 m tall tower with a tripod. All parameters except wind speed and wind direction are measured at a height of about 2 m from the ground surface. The surface consists of vegetation that naturally emerged after harvesting in July 1995 and small pine seedlings that were planted in February 1997. The site is drained with 1.2 m deep ditches that are 100 m apart. The average height of the emerging vegetation during the growing season is about 50 cm. The weather station continuously monitors data on air temperature, soil temperature, relative humidity, wind speed, wind direction, solar, and net radiation every 30 seconds and records the half-hourly readings as an average of sixty 30-second readings. Air temperature and relative humidity is recorded by Vaisala made HMP-45 sensors. REBS (Radiation & Energy Balance Systems) Q-7 radiometer sensor and LiCOR made Li-200 pyranometer sensors were used to record the net radiation and solar radiation, respectively. The station is also equipped with a sensor and a tipping bucket rain gauge. Soil heat flux sensors were installed in late 1998 to estimate that component of the total energy balance.

Table 1. Location, elevation, and period of data collection for three coastal weather stations in eastern North Carolina.

Location	Elevation, meters a.m.s.l	Latitude	Longitude	Vegetative Surface	Data Analysis Period
Carteret 7 Tract, Carteret County	3.0	34° 48' N	76° 40' W	Emerging Vegetation	October 1997 to December 1999
Parker Tract, Washington County	6.0	35° 50' N	76° 45' W	Pine forest	May 1996 to December 1999
TRS, Washington County	6.0	35° 50' N	76° 45' W	Grass	October 1997 to December 1999

The second station is located on a 22 m tall tower in the middle of a young pine forest also owned and managed by the Weyerhaeuser Company at Parker Tract in Washington County. This station was installed in late April 1996 to monitor weather parameters for studying ET and estimating REF-ET in forested conditions as a part of the ongoing 10,000 ha watershed scale study near the town of Plymouth (Amatya et al., 1999; 2000). The station is also equipped with the Campbell Scientific CR1 OX data logger and automatic sensors for recording the same parameters as at Carteret site, including an above canopy rain gauge. All sensors are installed in the galvanized steel tube arms projecting from the tower and kept about 2 meters above the tree canopy. The arms are raised every year after the winter season to keep the sensors about 2 meters above the canopy. Data collected and analyzed from this station were used in estimating REF-ET for a modeling study reported by Amatya et al. (1999).

The third station is located at Tidewater Research Station (TRS) near Plymouth in Washington County. This station was initially equipped with a CR1 0 data logger with automatic sensors for air temperature, relative humidity, solar radiation, wind speed, and wind direction, all mounted on a 2.5 m tall tripod above standard grass vegetation. Data from this station through 1994 have been reported by Amatya et al. (1995) for comparison of methods for estimating REF-ET in eastern North Carolina. Weather data from this station for 1995 through 1998 were used in estimating REF-ET required for water balance and modeling studies reported by Chescheir et al. (1995) and Amatya et al. (1999), respectively. In late September 1997, a pair of new sensors for monitoring solar and net radiation was installed side by side with the existing 3-year old solar radiation sensor for calibration. Data from these new sensors were recorded by an additional Campbell Scientific CR10X data logger. Wind speed sensors in the old station malfunctioned intermittently from late 1997 through 1998. Missing wind speed data were extrapolated from data collected at the adjacent Parker Tract station. A lightning strike in December 1998 completely destroyed the TRS weather station. A new CR1 OX weather station equipped with all sensors including a rain gauge was installed at this location in March 1999.

Starting March 1999 all three weather stations recorded the same type of weather data on 30-min intervals in the same format. All weather stations are serviced on a bi-weekly basis although data are downloaded every day by a telemetric system. Net and solar radiation sensors are sent to the factory for calibration on an annual basis. In order to maintain consistency in the type of sensors and data loggers used to collect radiation data, data only from October 1997 at the Carteret and TRS sites and from May 1996 at Parker Tract are analyzed in this study. Half-hourly weather data were averaged to obtain daily average parameters for each of these stations. Daily values for maximum and minimum temperatures, and average solar and net radiation were used in the further analysis. Days with missing data due to malfunctioning of the sensors were not considered in the analysis.

For the first objective, daily and monthly solar and net radiation data were compared using graphical plots and different statistics including t-tests. Secondly, daily solar radiation (R_s) data were computed for all three stations using the method suggested by Allen (1997) and the method suggested by Hargreaves-Samani (1982). Results from both of these methods were compared with measured daily averages. Allen (1997) introduced a new procedure for self-calibrating the following equation developed by by Hargreaves-Samani (1982) to estimate solar radiation:

$$R_s = K_r\,(T_{max} - T_{min})^{0.5}\,R_a \qquad \ldots\ldots(1)$$

Where, T_{max} and T_{min} are mean daily maximum and minimum air temperature (°C) for the period (generally one month); R_a is extraterrestrial radiation; and K_r is an empirical coefficient. Allen (1997) reported that a value of $K_r = 0.19$ for the coastal regions was suggested by Hargreaves (1994). This value of K_r was used in estimating R_s by Equation (1) for all three stations located. Daily values of extraterrestrial radiation (R_a) for all three stations were calculated by the methods suggested by Jensen et al. (1990) and reported by Amatya et al. (1995).

The self-calibrating procedure suggested by Allen (1997) involves calculation of R_s by applying Equation (1) on a daily basis with daily values of T_{max} and $T_{min,}$ an initial value of K_r and the calculated clear sky solar radiation (R_{so}). The daily values of clear sky radiation R_{so} were approximated using the relationship $R_{so} = 0.75\,R_a$ as suggested by Jensen et al. (1990). The values of K_r are altered by trial and error until the highest estimates of R_s using equation (1) contact the R_{so} envelope. Allen (1997) noted that since the Hargreaves-Samani method was basically developed for monthly periods, it may produce a greater prediction error when used on a daily basis. The reader is referred to Allen (1997) for more details of the self-calibration procedure.

To fulfill the third objective of this paper, daily measured values of net radiation (R_n) were plotted against solar radiation (R_s) for all available data through December 1998 for each of the three stations. Linear regression analyses were conducted on all data as well as summer (May to October) and winter (November to April) periods. Such relationships were obtained for all three stations. The calculated relationships with all data were first compared with the published relationship (Jensen et al., 1990):

$$R_n = -4.9 + 0.80 \cdot R_s \qquad \ldots\ldots\ldots\ldots\ldots\ldots(2)$$

Equation (2) was developed for Bermuda grass and clear sky conditions in North Carolina. Later the calculated relationships were used to predict the daily net radiation in 1999, which were compared with actual measured daily data at each of the three stations.

Statistical analyses were performed on data to evaluate the performance of the methods with measured data using various goodness-of-fit parameters. Standard t-tests were used to evaluate whether the daily mean solar and net radiation, measured at three stations with three different vegetation canopies, were significantly different at 1 % level of significance ($\alpha = 0.01$).

Results and Discussion:

Measured daily solar and net radiation data were averaged for each month to obtain average monthly data for the study period, November 1997 through December 1999 shown in Figure 1. Two months (January and February) of both the radiation data in 1998 and 5 months (August – December) of net radiation data in 1999 were not reliable at the Carteret site. So these months were excluded from the analysis. Both solar and net radiation data clearly showed the seasonal variation. The highest values (22 Mj/m^2/day for solar radiation and 16 Mj/m^2/day for net radiation) occurred during the months of June to August as expected. Values of solar and net radiation were as low as 6 Mj/m^2/day, and 2 Mj/m^2/day, respectively, in December. Solar radiation in September 1999 was lower than in October at all the three sites. This was probably due to several rainy/cloudy days during Hurricane Dennis and Floyd in September. Monthly solar radiation data observed at TRS site was consistent with the five-year (1990-94) average data reported by (Amatya et al., 1995). The seasonal variation was much larger than the variation among the sites as expected.

As seen from Figure 1 and Table 2, there is less variation in solar radiation compared to net radiation among three different sites. The mean annual ratio of daily solar radiation to extraterrestrial radiation for two years 1998 and 1999 varied only between 0.48 for TRS site to 0.52 for Parker Tract. These values are considerably lower than the values of 0.70-0.80 reported for semi-arid regions (Jensen et al., 1990). Mean daily solar radiation measured at Carteret site was the highest during most of the months because of its more southern location compared to Parker and TRS sites. Note that except during few months in the summer, extraterrestrial radiation around this latitude increases from north to the south (Table A.7, Jensen et al., 1990). The distribution (mean, standard deviation, median, and maximum) of daily solar radiation at Carteret site with emerging vegetation was more comparable to the Parker site (young pine forest) than the TRS site which has grass vegetation. The coefficient of determination, R^2 = 0.98 shows closer correlation of the solar radiation between Parker and TRS sites. These sites are separated by only 6 km, whereas the Carteret station is located more than 150 km to the south. Analysis using standard t-test showed no significant difference (α = 0.01) among the daily mean solar radiation observed at these three sites.

Table 2. Comparative statistics of daily measured solar and net radiation at three different stations. S.D. = standard deviation, C.V. = coefficient of variation.

	Solar Radiation, Mj/m^2/day					Net Radiation, Mj/m^2/day				
	Mean	S.D.	C.V.	Maximum	Median	Mean	S.D.	C.V.	Maximum	Median
Carteret	14.7	7.1	0.48	29.3	13.8	9.4	5.3	0.57	19.9	8.4
Parker	14.3	7.2	0.5	29.4	13.8	9.7	6.1	0.63	21.6	9.1
TRS	13.4	7.0	0.52	28.5	12.4	7.8	5.1	0.65	18.3	7.2

Both the highest mean daily and the maximum net radiation (R,) were observed for the Parker site (pine forest) followed by the Carteret site (emerging vegetation). The TRS site with grass vegetation yielded about 20 % lower mean daily R_n than Parker site and about 17 % lower than Carteret site. This is also consistent with earlier data for a 5-year (1988-92) period reported by Amatya et al. (1995) for a Carteret site with grass vegetation. The net radiation values observed at Carteret site in this study are generally 20 % higher than the 5-year average data for the grass. This is because the reflectance coefficient or albedo for short grass is higher than that for pine forest or for the emerging vegetation, which is usually much taller than grass. Jensen et al. (1990) reported the albedo value in the range of 0.20 to 0.25 with an average of 0.23 for most full cover green crops. Values in the range of 0.10 - 0.15 for coniferous (pine) forest and 0.19-0.25 for tall grass (e.g. alfalfa) were suggested by ASCE (1996) and Dunne and Leopold (1978). This is evident from the calculated ratio of net radiation to solar radiation, which was 68 % for pine forest (Parker) compared to only 58 % for grass (TRS). The calculated ratio of 64 % for Carteret with emerging vegetation was only 4 % less than that for pine forest. This indicates that the reflectance coefficient for emerging vegetation is higher than that for the pine trees but less than that for the grass. Standard t-test showed significant difference (a = 0.01) among daily mean net radiation measured above three vegetation types.

The estimated daily solar radiation (R,) determined by the self-calibration procedure (Eq. 1) suggested by Allen (1997) are plotted with time for the years 1998 and 1999 for Carteret, Parker Tract, and TRS sites in Figures 2, 3 and 4, respectively. Data show that the procedure was able to predict the distribution of solar radiation fairly well at all three sites in both of the years. However, the self-calibrated radiation values had less variation compared to the observed data. That was especially true in 1998. The procedure was unable to exactly predict clear sky solar radiation, which is consistent with the results of Allen (1997). The scatter plots of self-calibrated versus measured daily solar radiation for the two years are illustrated in Figure 5. These data indicate that the procedure overestimated smaller radiation values and underestimated larger values at the Carteret site. At two other sites, the estimated values were higher for the lower range and nearly randomly scattered around 1 :1 line for values > 10 Mj/m^2/day.

The self-calibration coefficient (K_r) values and the computed statistics between measured and self-calibrated solar radiation data for daily and monthly periods are presented'in Tables 3 and 4, respectively. These results are also presented for estimates using Hargreaves-Samani method which recommends a K_r value of 0.19 for coastal regions.

Table 3. K_r values and computed statistics between measured daily solar radiation and estimated solar radiation by self-calibration procedure and Hargreaves-Samani method. AADD = Average Absolute Daily Deviation and SEE = Standard Error of Estimate.

Station	Self-Calibratina method				Harareaves-Samani method			
	K_r	Estimated/ Measured Ratio	AADD (Mj/m²/day)	SEE (Mj/m²/day)	K_r	Estimated/ Measured Ratio	AADD (Mj/m²/day)	SEE (Mj/m²/day)
1998								
Carteret	0.16	1.51	4.39	5.95	0.19	1.80	5.39	**7.42**
Parker Tract	0.16	1.14	**3.30**	**4.28**	0.19	1.36	**4.34**	**5.61**
TRS	**0.15**	**1.63**	**3.53**	**4.62**	0.19	**2.07**	**6.17**	**7.42**
1999								
Carteret	0.16	1.27	**3.80**	**4.86**	0.19	1.50	**4.43**	**5.71**
Parker Tract	0.15	1.35	**3.23**	**4.32**	0.19	1.70	5.59	6.97
TRS	'0.15	1.34	**3.18**	**4.09**	0.19	1.70	**4.76**	**5.98**

The self-calibration procedure yielded K_r values between 0.15 and 0.16 only as opposed to 0.19 recommended by Hargreaves-Samani (1982) for coastal region. It is clear from Figures 2, 3, and 4 that K_r value of 0.19 will yield estimates of solar radiation exceeding the clear sky radiation (R_{so}) several days in the year at all three sites e.g. many more points in the plot will be above the R_{so} envelope. This indicates that using K, value of 0.19 for these sites in eastern North Carolina will overestimate solar radiation, and hence the REF-ET (PE) values using this solar radiation most of the times. This conclusion is supported by the computed monthly ratios of Penman-Monteith REF-ET to the Hargreaves-Samani PET, which was less than one for all months at Carteret and Plymouth sites (Amatya et al., 1995).

Table 4. K_r values and computed statistics between measured monthly solar radiation and estimated solar radiation by self-calibration procedure and Hargreaves-Samani method. AADD = Average Absolute Daily Deviation between estimated and measured data, SEE = Standard Error of Estimate.

Station	Self-Calibratina method				Harareaves-Samani method			
	K_r	Estimated/ Measured Ratio	AADD (Mj/m²/day)	SEE (Mj/m²/day)	K_r	Estimated/ Measured Ratio	AADD (Mj/m²/day)	SEE (Mj/m²/day)
1998								
Carteret	**0.16**	**1.16**	1.99	3.14	0.19	1.37	**4.76**	**5.75**
Parker Tract	0.16	1.11	1.20	1.46	0.19	1.31	4.10	**4.38**
TRS	0.15	1.15	1.88	2.10	0.19	1.46	**6.10**	**6.67**
1999								
Carteret	0.16	1.03	0.99	1.35	0.19	1.23	**3.37**	**3.78**
Parker Tract	0.15	1.09	1.38	1.98	0.19	1.38	5.13	**6.47**
TRS	0.15	1.07	0.99	1.14	0.19	1.36	**4.76**	**5.12**

The average SEE for all sites in both years by Hargreaves-Samani method was 6.52 Mj/m²/day, which is about 40 % higher than 4.67 Mj/m²/day calculated for self-calibrating method. Other computed statistics in Table 3 also showed that the Hargreaves-Samani method was less accurate than the self-calibration procedure at all three sites in both the years. The computed average SEE of 4.67 Mj/m^2/day by self-calibration method for 6 site-years of data is about 12 % higher than the average SEE reported by Allen (1997) for 7 locations in the U.S. The errors were relatively less in 1999 than in 1998 at all three sites. The errors were highest for Carteret site in both the years.

Similar statistics presented in Table 4 for monthly periods show that both the self-calibrating and Hargreaves-Samani methods are more accurate for monthly than for daily periods. This was expected as Equation (1) was developed and recommended for monthly time periods. The self-calibration method resulted in much smaller errors than Hargreaves-Samani. The average SEE value of 1.86 Mj/m^2/day was still higher than the value of 1.3 Mj/m^2/day reported by Allen (1997). One of the reasons for the larger errors in this study compared to Allen (1997) may be due to the fact that the measured solar radiation R_s was not adjusted in this study. In the study by Allen (1997), the R_s was adjusted (mostly on higher side) to force the upper surface of measured R_s to match computed clear sky radiation R_{so} envelope. The average ratio of estimated and measured solar radiation for six site-years was 1 .10 for self-calibration method. This indicates that the method with given K_r value overestimates the measured monthly data by 10 percent on average. These errors may have also been contributed by the use of the approximate method to estimate clear sky radiation R_{so} as compared to the more complex method used by Allen (1997). In general, these results show that the self-calibrating method is reliable for estimating monthly solar radiation, and that it can be used for estimating monthly REF-ET (PE) used in hydrologic models.

Measured daily solar radiation and net radiation are plotted in Figure 6 for the Carteret, Parker and TRS sites. Carteret and TRS sites cover data from October 1997 through December 1998. Data from May 1996 through December 1998 were used for Parker Tract. The linear regression relationship of net radiation versus solar is also plotted for each of the sites in Figure 6. Net radiation predicted by daily net versus solar radiation relationship using Equation (2) for Bermuda grass in North Carolina (Jensen et al., 1990) is also plotted in Figure 6 for comparison.

Data from all the sites seemed to be fairly well correlated with R^2 value exceeding 0.85. The regression parameters were also significant at a = 0.05. The regression equation for each of the sites is shown in the figure. However, the relationship for Parker Tract was somewhat weaker (R^2 = 0.85) compared to two other sites (R^2 = 0.96 and R^2 = 0.92) due to large scatter of R_n data for R_s values smaller than 22 Mj/m^2/day. When data were examined by individual years, it was found that measured R_n values in late winter (December - March) were much lower than other R_n values for the similar R_s values during other periods of the year. This indicates that there may be seasonal differences in net radiation measured on pine trees, which will be discussed below in more detail. The slope of the regression line for Parker Tract was 0.75, which is close to that of the published data (0.80). However, the intercept was lower so that Equation (2) from literature would have consistently underestimated R_n for Parker Tract on pine forest (Figure 6), except for the periods of December-March as shown above. The average daily R_n for the 1996-98 period was only 7.5 Mj/m^2/day using Equation (2) compared to 10.2 Mj/m^2/day by the regression relationship.

The regression relationship was the strongest for the Carteret site on emerging vegetation with the highest R^2 = 0.96 and the smallest SEE = 1 .01 Mj/m^2/day. It is evident from the plot in Figure 6 that Equation (2) would largely underestimate R_n in the lower range of solar radiation. The underestimation, however, would not exceed 4.0 Mj/m^2/day. Accordingly, the average daily net radiation by equation (2) was only 5.8 Mj/m^2/day compared to 8.3 Mj/m^2/day estimated using regression relationship. The data for this site did not indicate the seasonal difference observed for the Parker Tract.

There was slightly larger variation in scatter diagram for TRS site compared to Carteret site (Figure 6). However, the statistical parameters of regression indicate that this relationship was stronger than that for Parker Tract. The largest difference in slope between the regression and Equation (2) was found for this site. Data in Figure 6 indicate that use of Equation (2) would have produced large underestimates in the lower range of R_s and slight overestimates in the highest range of R,. The average daily net radiation of 6.0 Mj/m^2/day estimated using Equation (2) was only 20 % lower than 7.5 Mj/m^2/day obtained from the regression relationship.

Based on these analyses it was concluded that Equation (2) underestimates net radiation on coastal plain sites with the types of vegetation analyzed here. However, with some correction for intercept, Equation (2) could be applied on pine forests in coastal North Carolina.

The regression models based on measured data through 1998 for each site were applied to predict daily net radiation from measured daily solar radiation in 1999. Data beyond July was not reliable for Carteret and hence not used for the analysis. The predictions of daily net radiation by the regression models were in good agreement with measured data at all three sites, except during the winter when model predictions were higher than the measured data (Figure 7). There was also a tendency of underprediction of measured data during the peak summer days 181 to 243 (July and August) at all three sites. Scatter plots of measured and predicted daily values are shown in Figure 8. The corresponding statistics between measured and predicted values are given in Table 5. The larger mean values for the predicted data and the positive values of ADD parameter indicate that the regression models tend to overpredict net radiation at all three sites. The predictions were the best for Carteret site, which had emerging vegetation. The mean and standard deviation of the predicted data were in close agreement with measured data (Table 5), indicating that the distributions are similar. This is also shown by the scatter plot distributed around the 1 :1 line (Figure 8), and by the highest R^2 value (0.95) and the least SEE and AADD. Unfortunately, this site had only 212 days of data from January to July. The model predictions were poorest at the TRS site, which had the lowest R^2 value (0.80) and the largest SEE, AADD, and ADD values.

Table 5. Computed statistics between measured daily net radiation and net radiation predicted by regression models. S.D. = Standard Deviation, ADD = Average Daily Deviation between predicted and measured data, AADD = Average Absolute Daily Deviation between predicted and measured data, SEE = Standard Error of Estimate.

Station	Measured Mean	Measured S.D.	Predicted Mean	Predicted S.D.	ADD	AADD	SEE	R^2
	Mj/m^2day		Mj/m^2day		Mj/m^2day			
Catteret	10.8	5.6	10.9	5.2	0.13	1.06	1.25	0.95
Parker Tract	9.4	6.1	9.7	5.4	0.24	1.58	1.88	0.88
TRS	7.2	5.9	7.7	4.5	0.50	2.10	1.98	0.80

Effects of seasonality on the measured relationships were examined by splitting all the data through 1999 into summer and winter periods. Data for summer and winter periods are plotted for all three sites in Figure 9. These plots indicate that the relationships between net and solar radiation are stronger in the summer than in the winter for all the sites. There was not much difference between winter and summer for Carteret site, which had R^2 and SEE values of 0.96 and 0.89 for summer and 0.95 and 0.93 for winter, respectively, Surprisingly, data in Figure 9 indicated the largest variation in the scatter plot for Parker Tract during the winter. The variation was such that as if there were two different relationships with similar slopes but different intercepts. In-depth examination of all data through 1999 indicated somewhat different results for winter and summer seasons on this pine forest site. For example, the winter data did not seem to start until approximately in mid-December in each of the years 1996, 1997, 1998 and 1999. Thus the winter season was very short ending somewhere in mid-March for 1997 and 1998 and even shorter ending in mid-January in 1999. This may be true because summer and fall of 1998 followed by the winter and spring of 1999 were all very warm and dry with lower than normal rainfall (Amatya et al., 2000). Apparently, radiant energy might have tended to increase even in late January in 1999 compared to other years. Thus the fewer scatter plots with lower intercept (lower R_n values) represented the short winter period (not shown). However, there was a weak correlation for the winter period compared to the data from the summer period. One likely reason is that during that dormant period the leaf area index (LAI) of the pine trees is low with more open canopy. As a result the radiometer may likely be capturing effects of understory vegetation which usually has higher albedo (reflectance coefficient) than pine tree canopy. These results tend to support the recent findings of Wilson et al. (2000). The authors reported that over a year, net radiation at the forest floor was 21.5 % of that above the canopy, but this proportion was not constant, primarily because of the distinct phenological stages separated by the emergence and senescence of leaves of the temperate deciduous forest they studied. The dominant response to seasonal changes in net radiation was through corresponding changes in the sensible heat flux, which along with net radiation peaked just before leaf emergence.

For the Parker Tract site, R^2 and SEE values were 0.70 and 2.63 for the winter and 0.96 and 0.98 for the summer, respectively. The difference between winter and summer results at the TRS site was much less compared to them at the Parker Tract, although they are located only 6 km apart. The R^2 values for summer and winter were 0.95 and 0.88, respectively, for TRS. SEE values for this site for the summer and winter were 0.84 and 1 .18, respectively. These results indicate that net radiation measured above young pine trees may respond differently during long summer and short winter periods in contrast to the shorter vegetation.

Summary and Conclusions

Air temperature, relative humidity, wind speed, solar radiation and net radiation were continuously measured using automated sensors with a CR1 OX data logger at three weather stations located about 150 km apart within 34° 48' N to 35° 50' N latitude in eastern North Carolina. These variables were measured at each weather station for at least a 26-month period between the years 1996 and 1999. The Carteret site had an emerging vegetation following pine harvest in 1995 and replanting in 1997. Vegetation at the Parker Tract site was a young (8-year old) pine forest, while Tidewater Research Station (TRS) site was on grass.

Analysis of the data indicated that the mean annual ratio of daily solar to extraterrestrial radiation at these three coastal sites ranged between 0.48 to 0.52, and was considerably lower than that for semiarid regions. Average daily solar radiation was the highest for Carteret site (emerging vegetation), which is located further south than the other two sites. The values were lowest for TRS site on grass. However, a standard t-test showed barely any difference (α = 0.01) between daily solar radiation measured at the sites.

Mean daily net radiation was the highest at the Parker Tract (pine forest) followed by Carteret (emerging vegetation) and the TRS site (grass). This pattern was attributed to the effects of albedo, a radiation reflectance coefficient characteristic of the surface above which net radiation is measured. The value is much smaller (0.1 O-O.1 5) for pine forest than for short grass (0.19-25). Accordingly, the mean daily ratio of solar to net radiation was 0.68 for pine forest at Parker and only 0.58 for grass at TRS site.

Results of testing a self-calibration procedure for estimating daily and monthly solar radiation using daily maximum and minimum temperatures showed that the method is more accurate and reliable for monthly periods than for the daily periods. The average absolute daily difference (AADD) and standard error of estimate (SEE) parameters indicate that this method is still more accurate than Hargreaves-Samani method for both daily and monthly periods. Analysis of the data revealed that Hargreaves-Samani's recommended calibration coefficient of 0.19 for coastal regions is higher than the ones (0.16) obtained by the self-calibration procedure of Allen (1997). Hence, in the absence of measured data, Allen's method with coefficient of 0.15-0.16 may be recommended for estimating solar radiation, which can then be applied to estimate potential evaporation for water balance and modeling studies in the coastal Carolinas.

Examination of relationships for daily measured solar and net radiation data indicated a strong correlation for each of the sites, with the strongest for the Carteret site. Results also revealed that such relationships published in the literature for North Carolina may well underestimate daily net radiation, and hence the potential evaporation. Statistical tests of these regression models showed that the models may be good predictors of net radiation to be used in estimating REF-ET (PE) with physically based P-M methods. When analyzed on a seasonal basis, data showed no difference between winter (November-April) and summer (May -- October) at least at Carteret site (emerging vegetation) There were clear differences, however, for the Parker Tract site, which had a 8-year old pine forest. In-depth examination of the seasonal data from Parker Tract showed that a strong correlation existed for a long period from about Mid-March to Mid-December. However, the data for the short winter season (mid-December to mid-March) was highly variable with a very poor correlation. It was speculated that such a pattern occurs for a large canopy due to increased LAI during the growing season. After LAI falls in the dormant season, net radiation was probably influenced by the reflectance coefficient of various types of understory grass and black organic soils. Methods tested herein can be useful for estimating REF-ET used in water balance and hydrologic modeling in the absence of measured radiation data in the coastal Carolinas. The authors, however, suggest that these methods for estimating radiation be further tested with multiple site-years of data from humid coastal plains.

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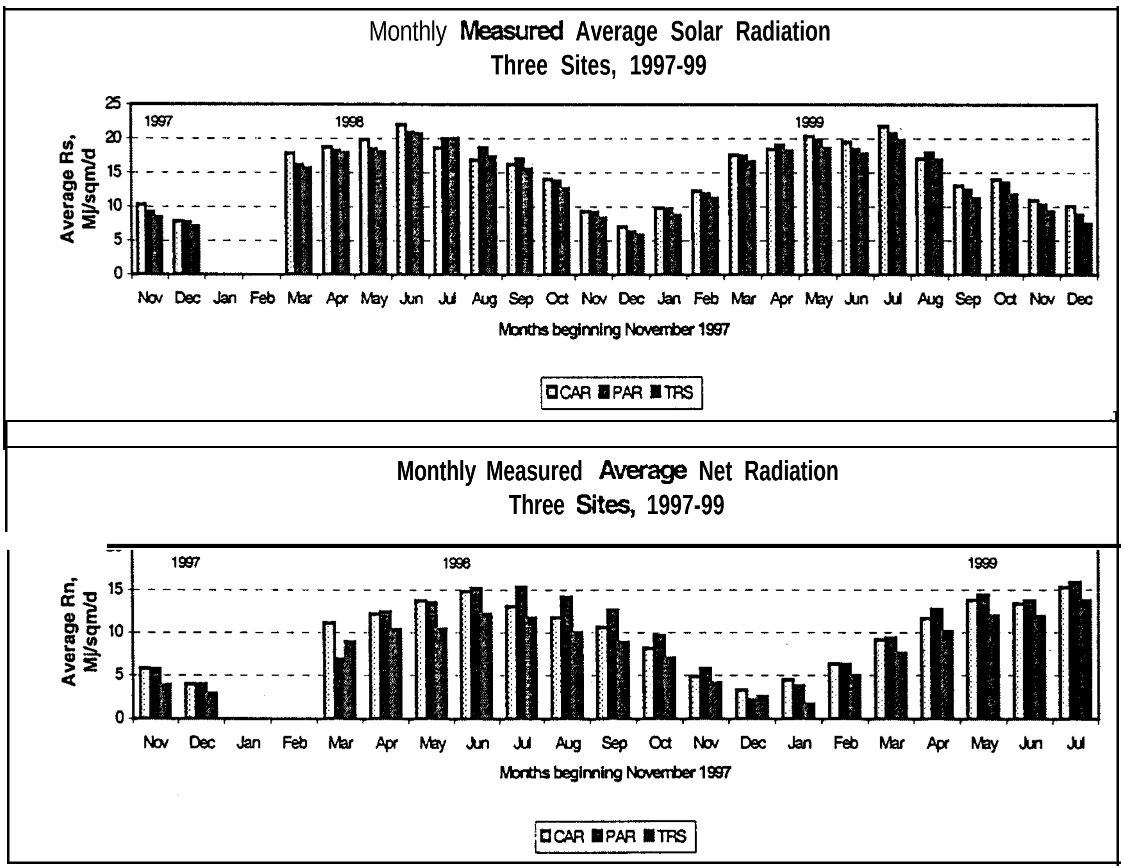

Figure 1. Monthly Average Solar (Top) and Net (Bottom) radiation measured at three weather stations. CAR = Carteret on emerging wetland vegetation, PAR = Parker Tract on pine forest, and TRS = Tidewater Research Station on grass.

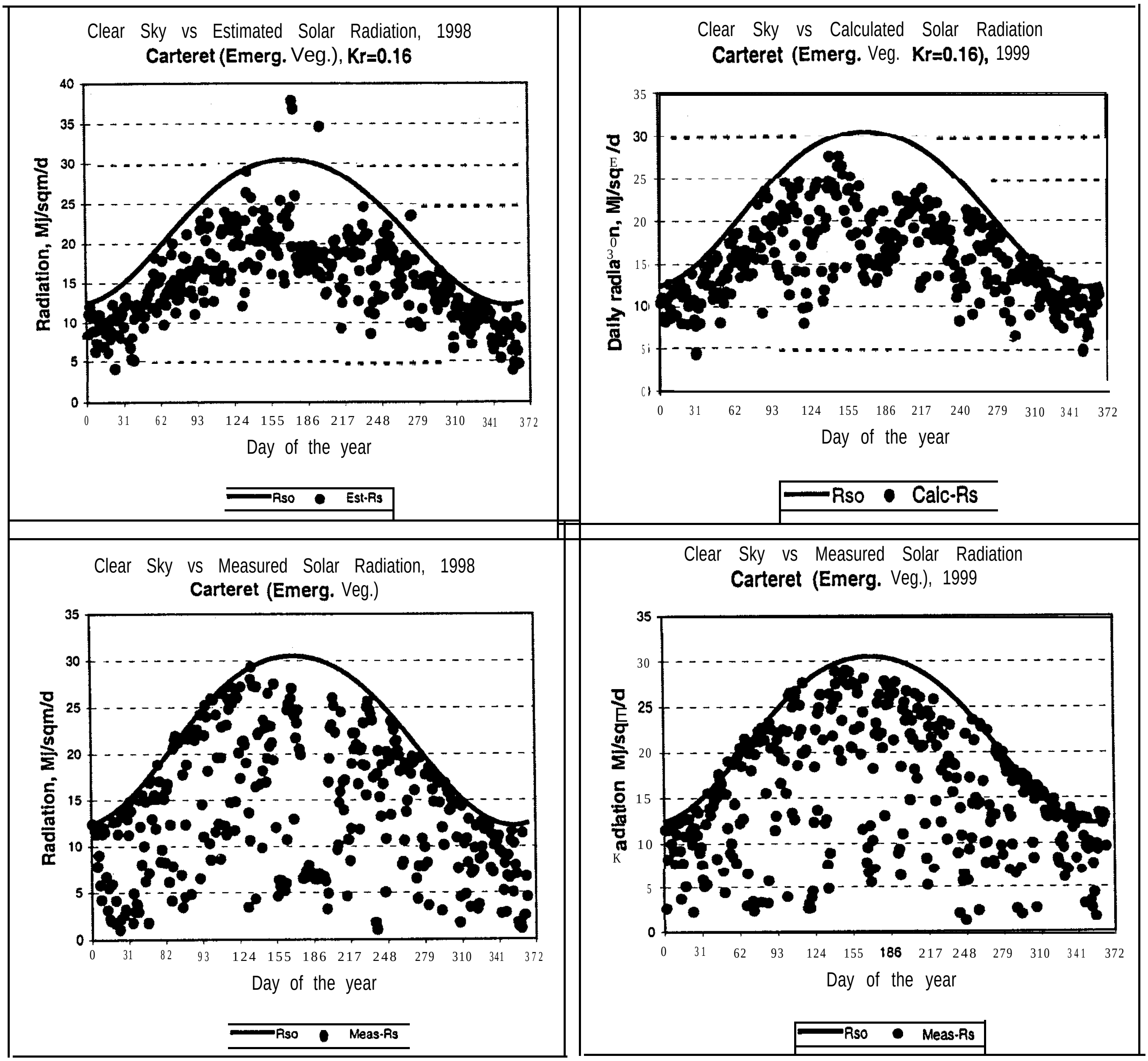

Figure 2. Mean daily solar radiation estimated by self-calibiation procedure Equation (1) versus clear sky radiation (R_{so}) for 1998 and 1999 at Carteret weather station on emerging vegetation.

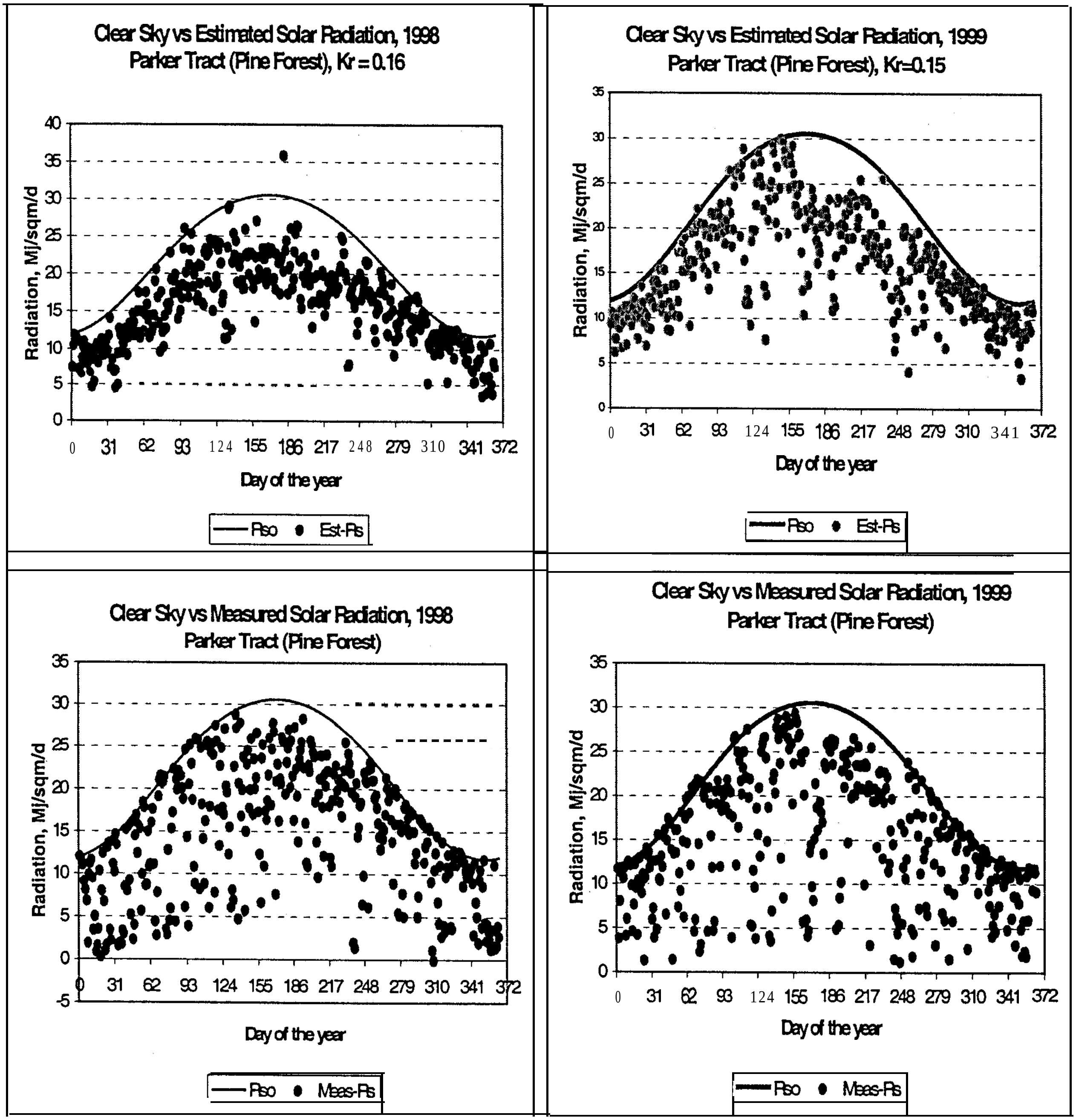

Figure 3. Mean daily solar radiation estimated by self-calibration procedure Equation (1) versus clear sky radiation (R_{so}) for 1998 and 1999 at Parker Tract weather station on pine forest.

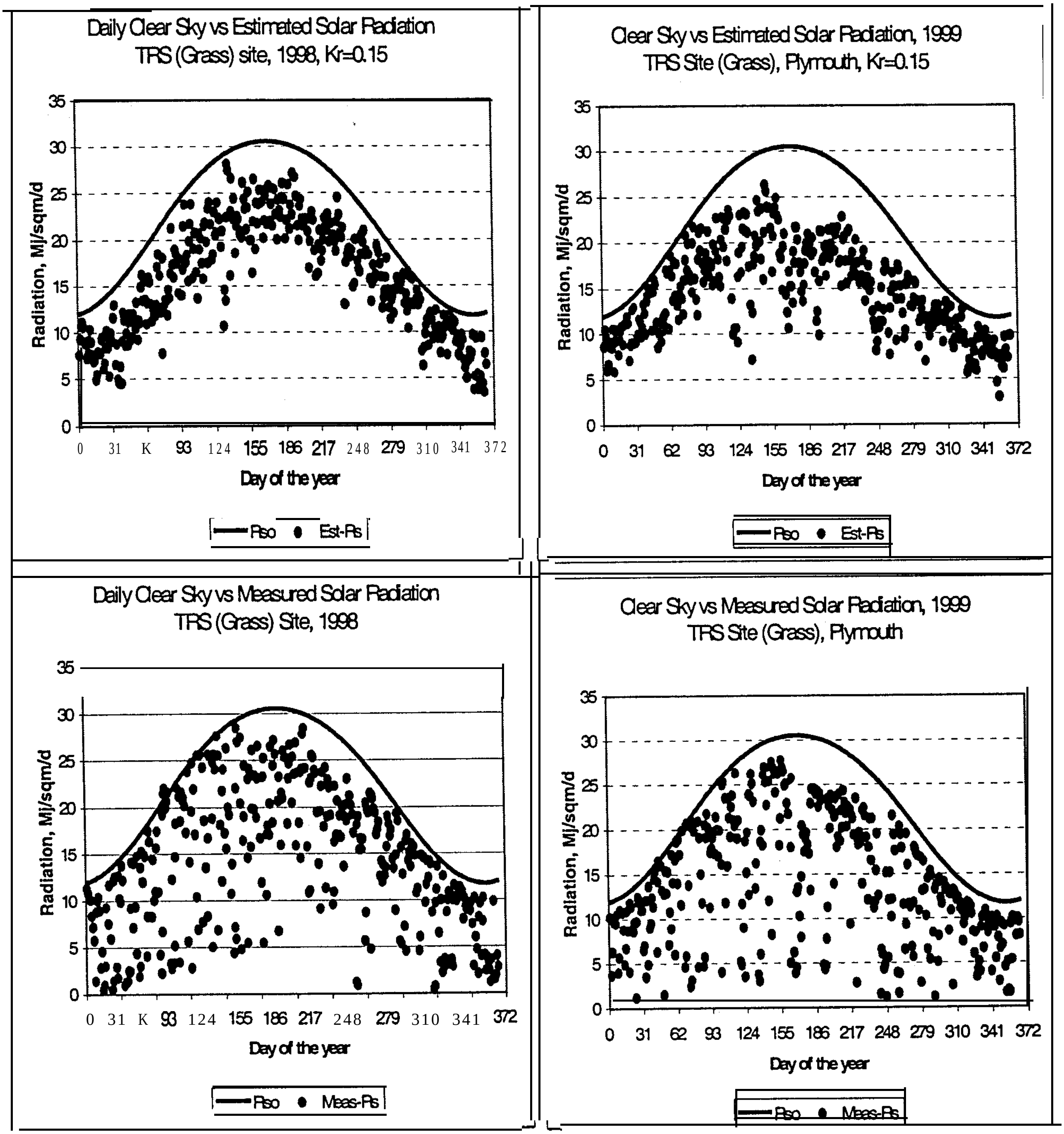

Figure 4. Mean daily solar radiation estimated by self-calibration procedure Equation (1) versus clear sky radiation (R_{so}) for 1998 and 1999 at TRS weather station on grass.

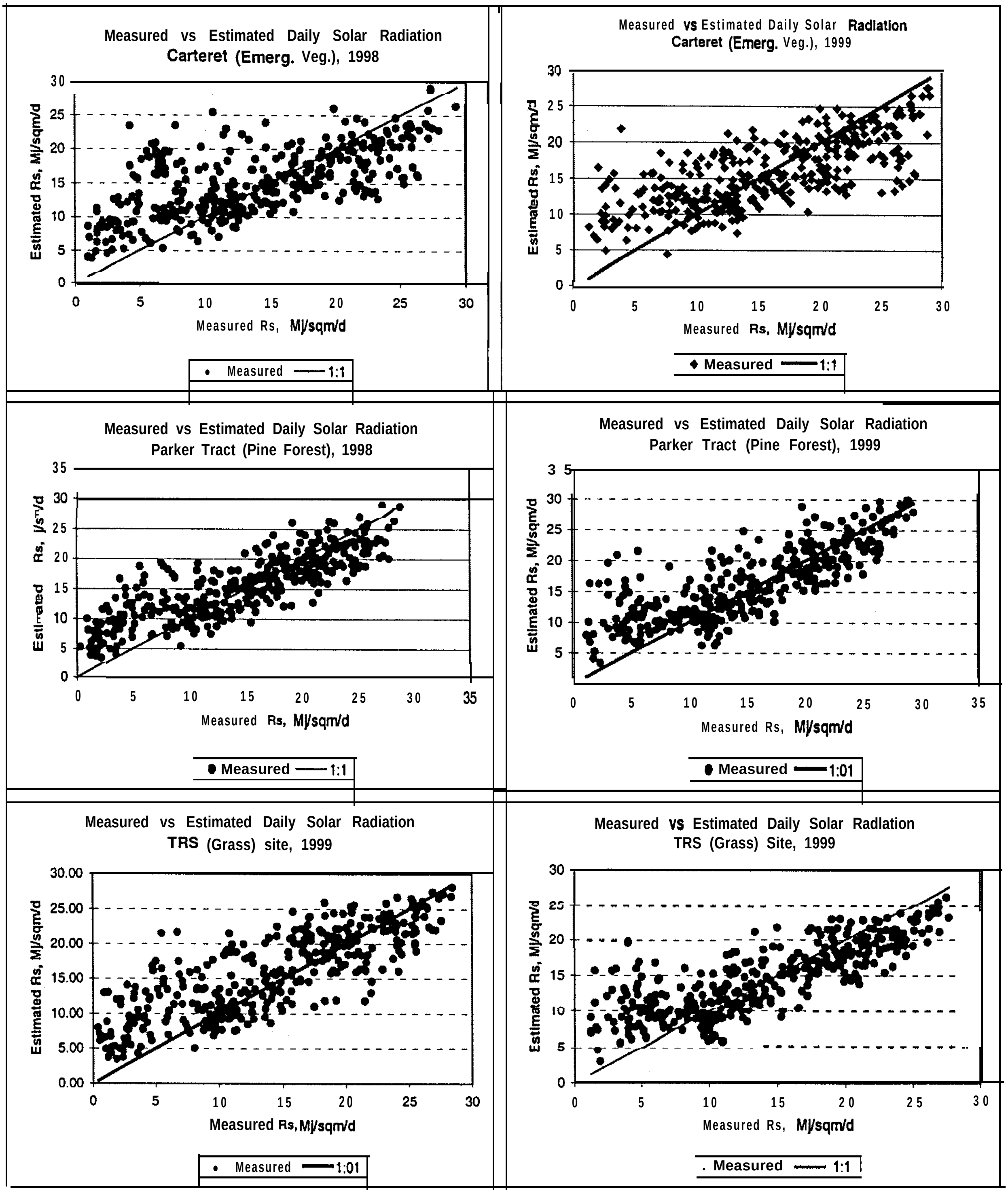

Figure 5. Measured vs Estimated daily solar radiation using eq. (1) by self-calibration procedure for two years at Carteret (top), Parker Tract (middle), and TRS (bottom) weather stations.

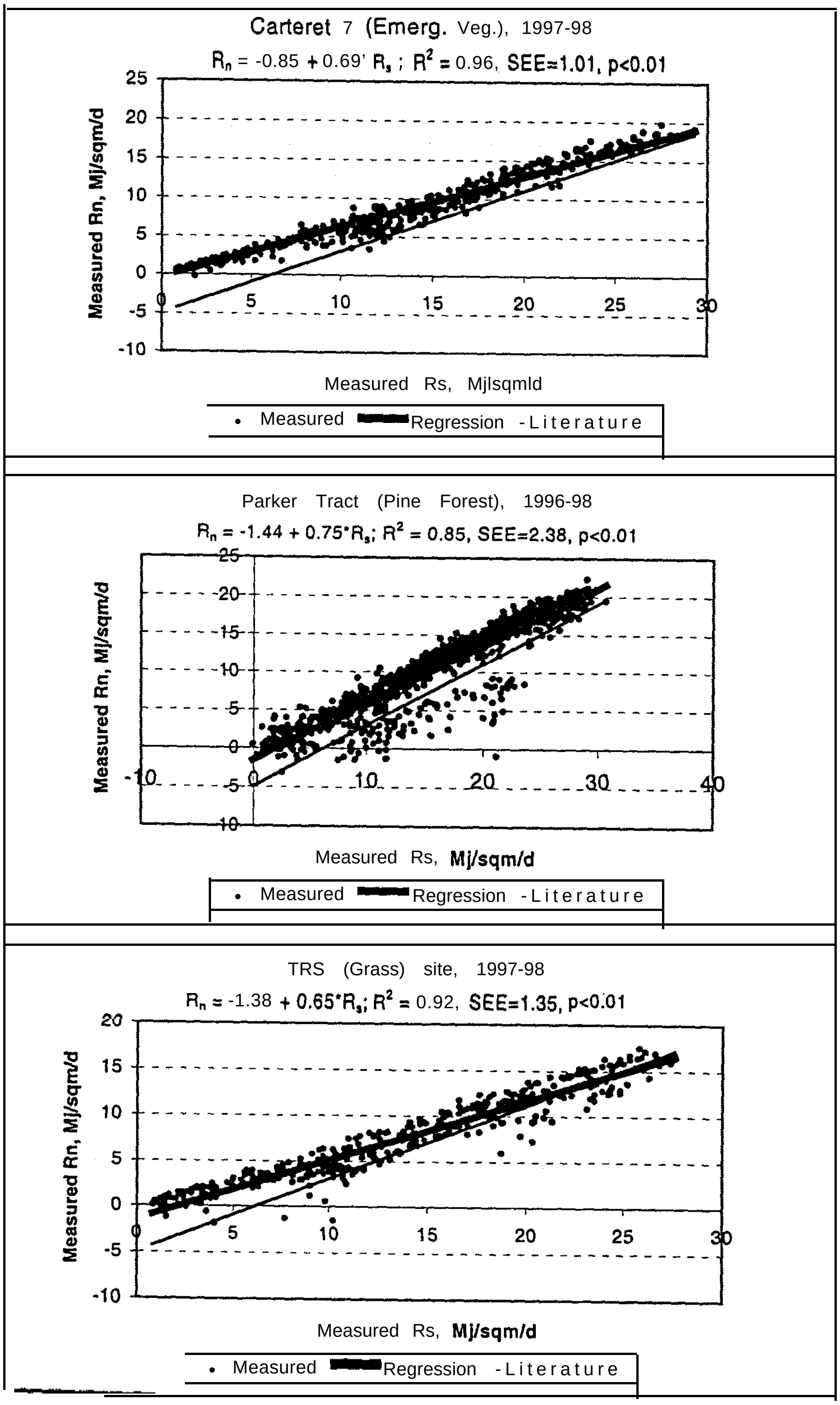

Figure 6. Measured, regression and literature (Jensen et al., 1990) published daily net (R_n) versus Solar (R_s) radiation for Carteret (top) on emerging vegetation, Parker Tract (middle) on pine forest, and TRS (bottom) *on* grass sites in eastern North Carolina.

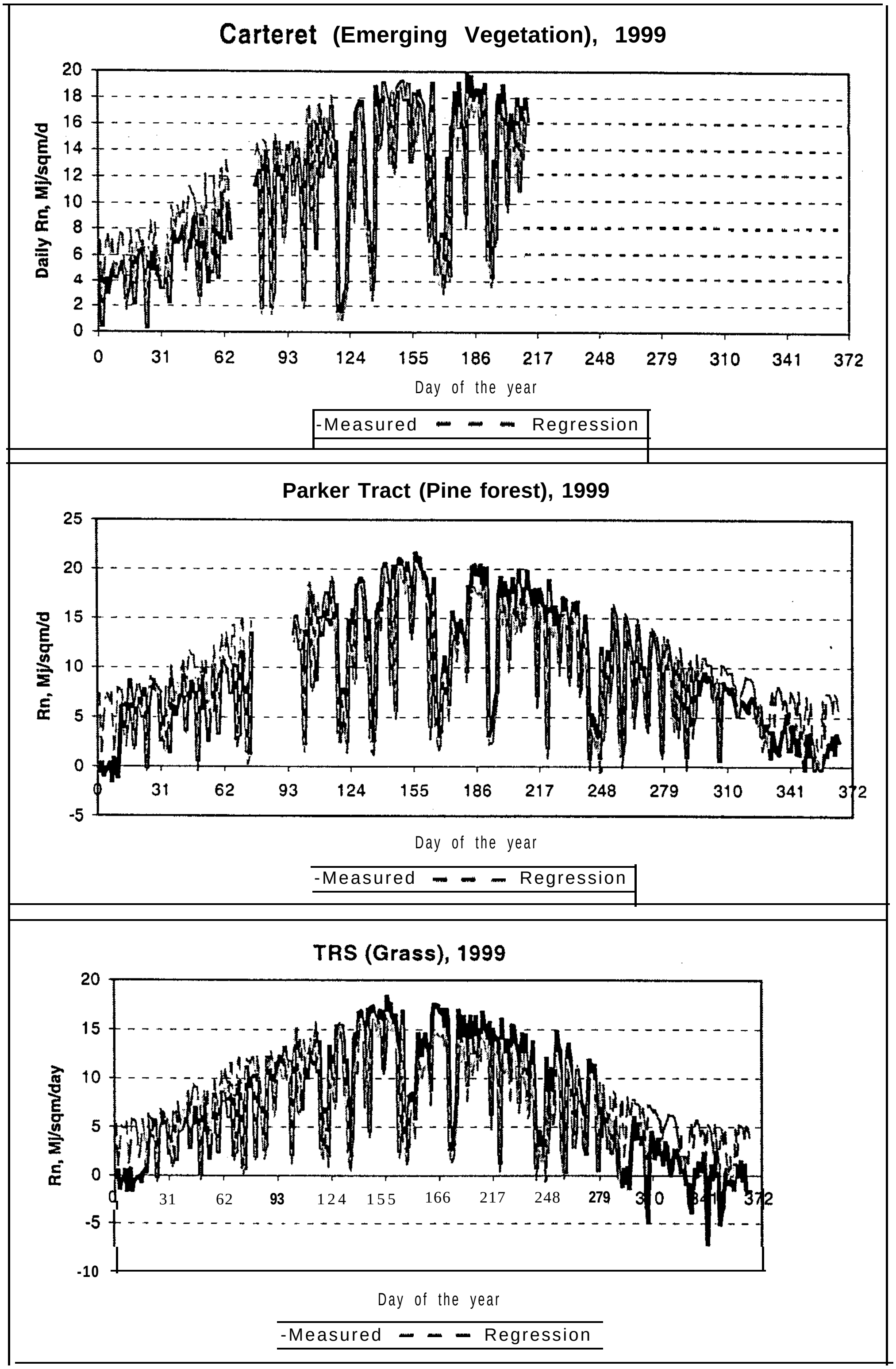

Figure 7. Measured and Regression Equation predicted daily net radiation for 1999 at Carteret (top), Parker Tract (Middle), and TRS (bottom) sites.

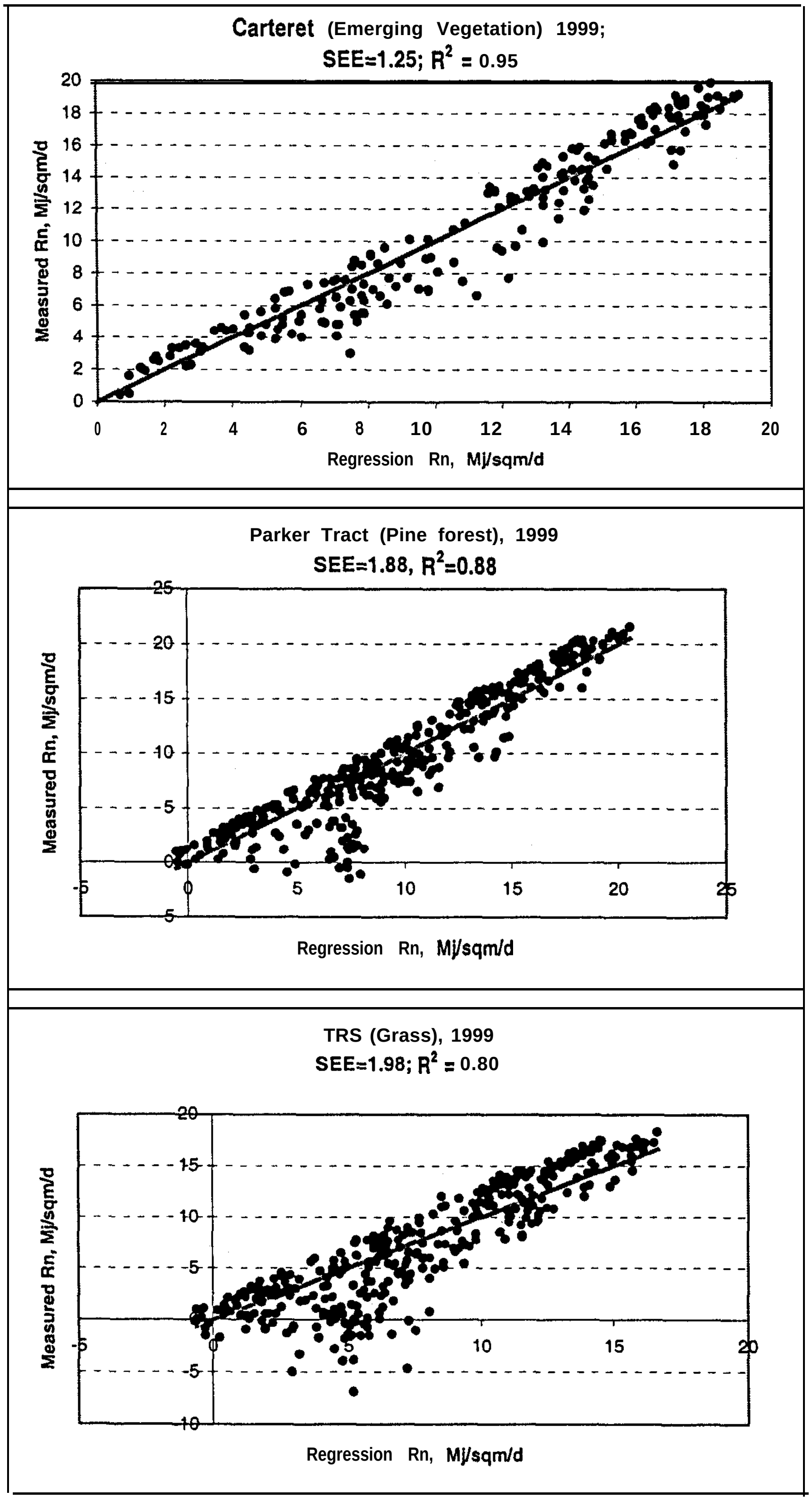

Figure 8. Scatter plot of regression predicted net radiation with measured data for 1999 at Carteret (top), Parker Tract (middle) and TRS (bottom) sites. Solid line is 1:1 line for regression predicted data.

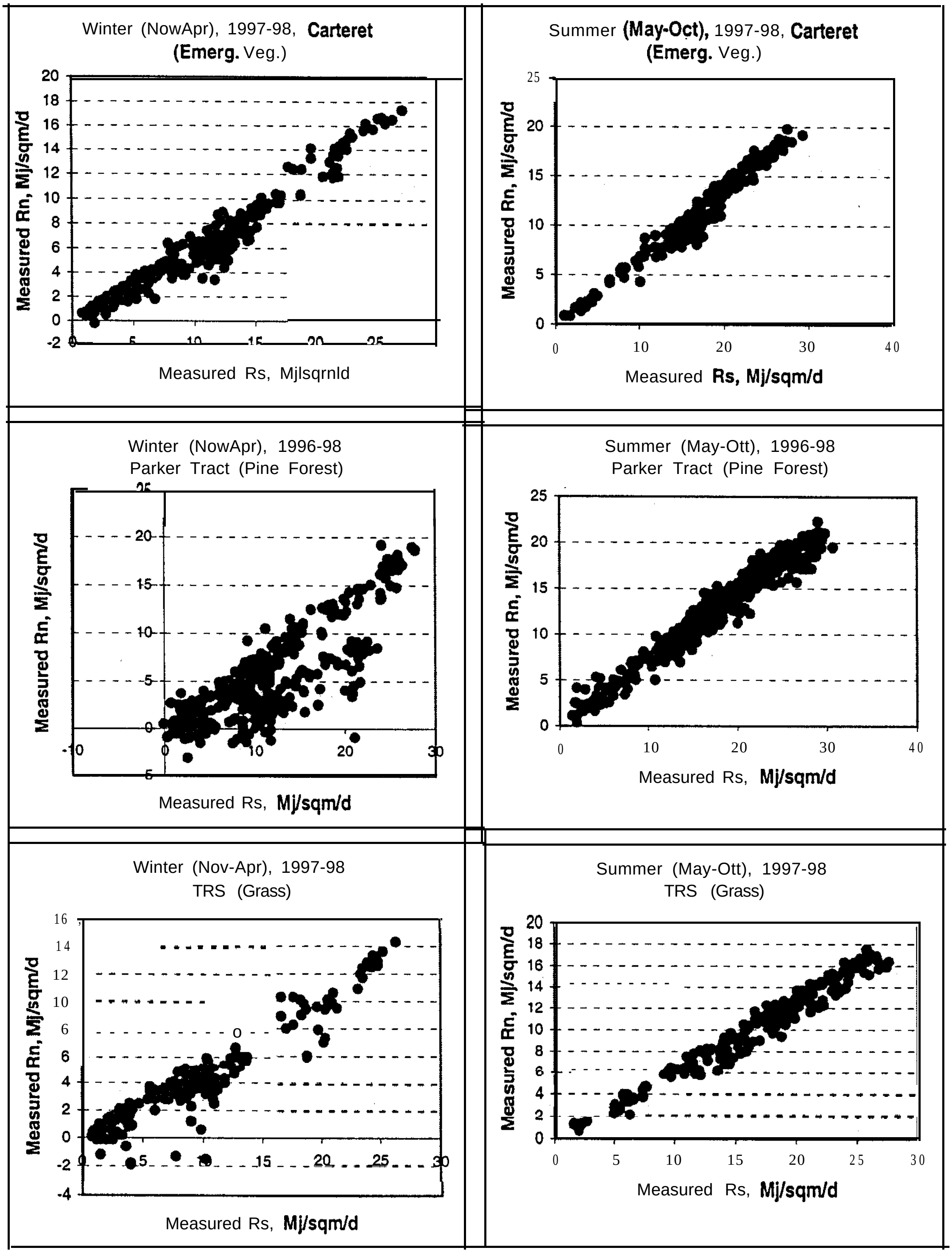

Figure 9. Scatter plot of measured daily net radiation and solar radiation for winter (left) and summer (right) for Carteret (top), Parker Tract (middle) and TRS (bottom) sites.